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LA-UR-21-21103
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Title: Spot-size Enlargement due to Injector Beam Spill

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Intended for: Report

Issued: 2021-02-08

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Spot-size Enlargement due to Injector Beam Spill

Carl Ekdahl

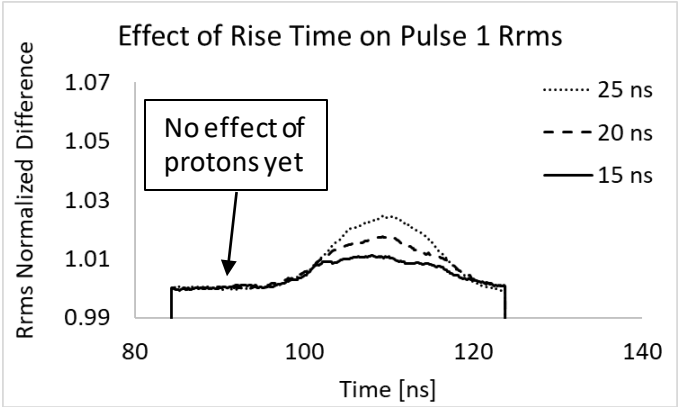
SWS Presentation
December, 2020

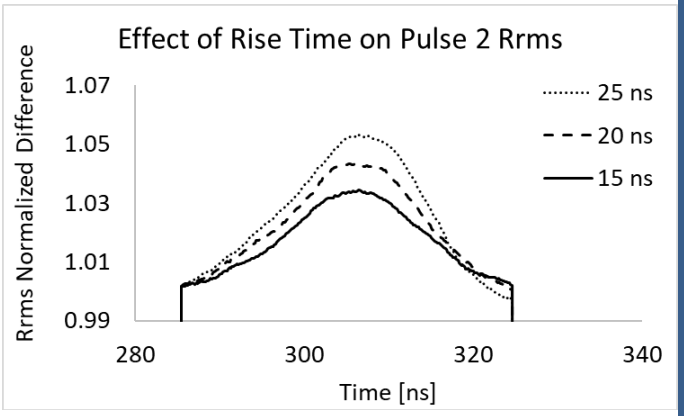
Los Alamos NATIONAL LABORATORY EST. 1943

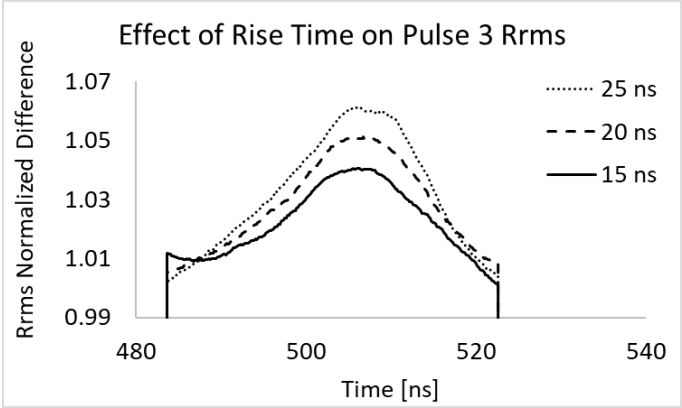
Trevor has used LSP simulations of beam neutralization by ions produced by beam spill to calculate the resulting time-resolved change in the beam rms radius at the injector exit.

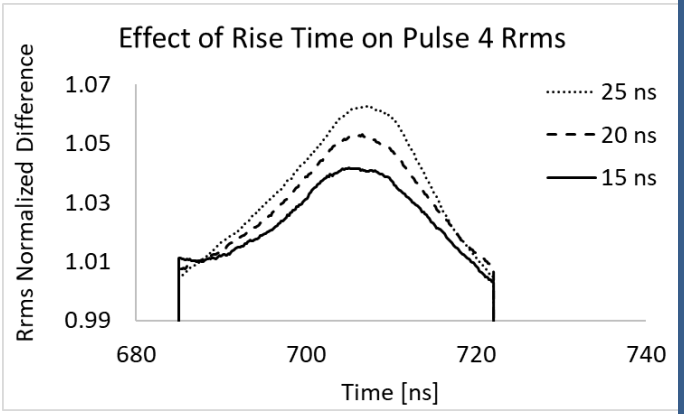
With Protons
Logistics Function

Rrms Variations:
- Long Time
- Small Amplitude

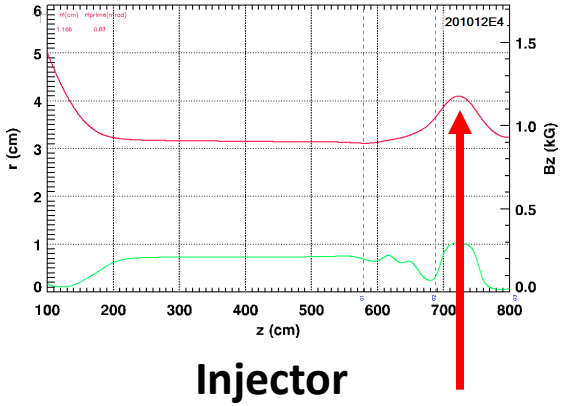




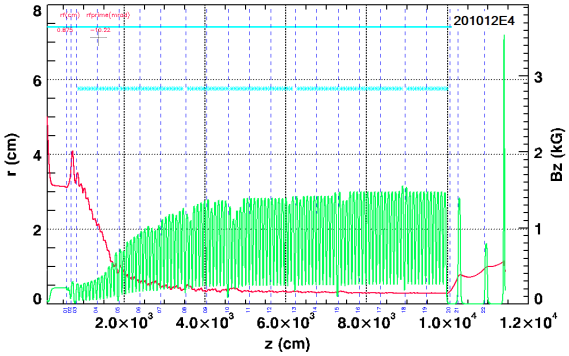




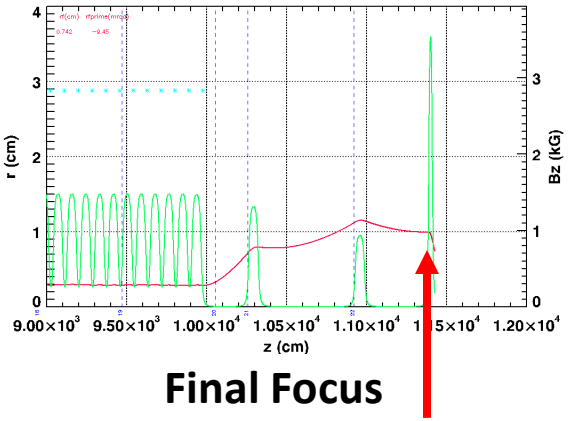
TRANSPORT style matrix optics can be used to deduce the affect of beam spill on radiography source-spot size.



Injector



Transport



Final Focus

$$\mathbf{x_0} = \begin{bmatrix} x_0 \\ x_0' \end{bmatrix} = \begin{bmatrix} x_0 \\ 0 \end{bmatrix}$$

LSP result here

$$\mathbf{x_{FF}} = \mathbf{R}\mathbf{x_0}$$

$$\begin{bmatrix} x_f \\ 0 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \begin{bmatrix} x_0 \\ 0 \end{bmatrix}$$

$$\Rightarrow R_{12} = R_{21} = 0$$

$$\mathbf{x_{FF}} = \begin{bmatrix} x_f \\ x_f' \end{bmatrix} = \begin{bmatrix} x_f \\ 0 \end{bmatrix}$$

This is point-to-point, parallel-to-parallel imaging, and since the determinant of the transfer matrix must be unity, it follows that

$$\mathbf{R} = \begin{bmatrix} R_{11} & 0 \\ 0 & 1/R_{11} \end{bmatrix}$$

TRANSPORT matrix optics can calculate the transformation of phase space from the injector exit to the final focus entrance.

- At the injector exit beam-envelope maximum the phase-space ellipse is upright.
- Tuning the DST for a waist at the final-focus entrance, ensures an upright phase-space ellipse at that location.
- The beam phase-space ellipse is transformed according to

$$\boldsymbol{\sigma}(FF) = \mathbf{R}\boldsymbol{\sigma}(Inj)\mathbf{R}^{\mathrm{T}}$$

where

$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xx'} \\ \sigma_{x'x} & \sigma_{xx} \end{bmatrix} = \begin{bmatrix} 2\langle x^2 \rangle & 0 \\ 0 & 2\langle x'^2 \rangle \end{bmatrix}$$

for upright ellipses

It follows that a fractional perturbation of beam size at the injector exit will result in the same fractional perturbation at the final-focus entrance.

Matrix optics provides a simple relation between the envelope maxima at the injector exit and at the entrance to the final focus.

- In particular, the fractional perturbation due to ion focusing is the same at both positions, to first order.

- If the beam size at the final focus magnet is optimized to minimize the radiographic source spot, the spot-size effect due to the ion-focus perturbation can be deduced.

The downstream transport can be tuned to minimize the radiographic source-spot size.

- **Many physical effects contribute to the size of the source spot.**
  - **Beam emittance**
  - **Beam space charge**
  - **Final focus solenoid aberrations (e.g., spherical, chromatic, etc.)**
  - **Beam motion (e.g., BBU, corkscrew, etc.)**
  - **Beam-target interactions (e.g., space-charge shorting, ion focusing)**

- **The minimum spot size can be deduced from the quadrature sum of sizes resulting from each effect in isolation.**
  - **Discussed by D. J. Lawson as optimization of convergence angle. This approach was used in an analysis of DARHT-I by Trevor.**
  - **Discussed by Y. J. Chen as optimization of beam size entering final focus. This is the approach taken herein.**

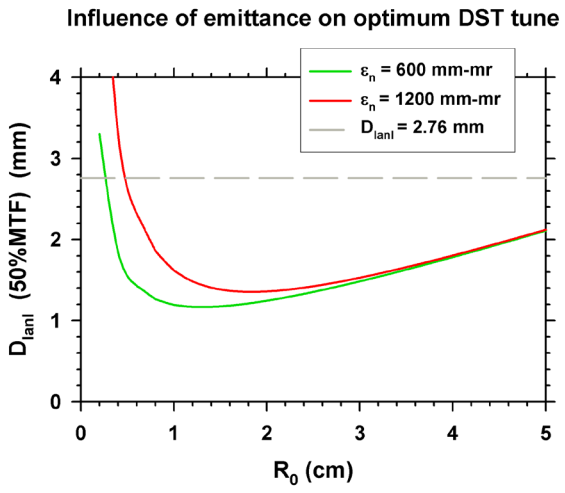
In the absence of beam target effect, spot size can be optimized if there is sufficient knowledge of beam parameters.

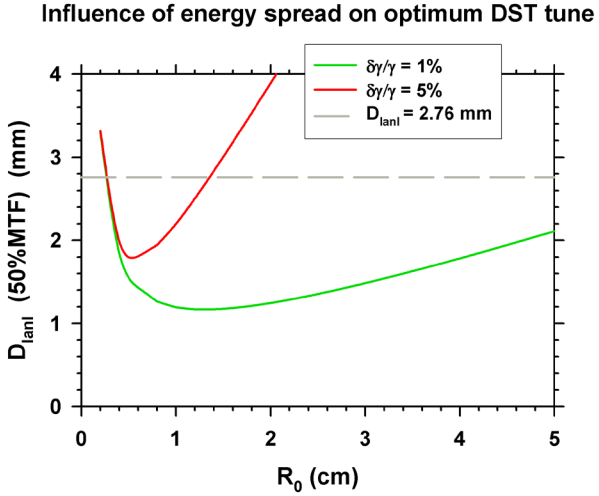
$$r_{spot}^2 = \left(\frac{\varepsilon_n f}{\beta\gamma R_0}\right)^2 + \sum R_{aberrations}^2 + \sum R_{motion\ blur}^2$$

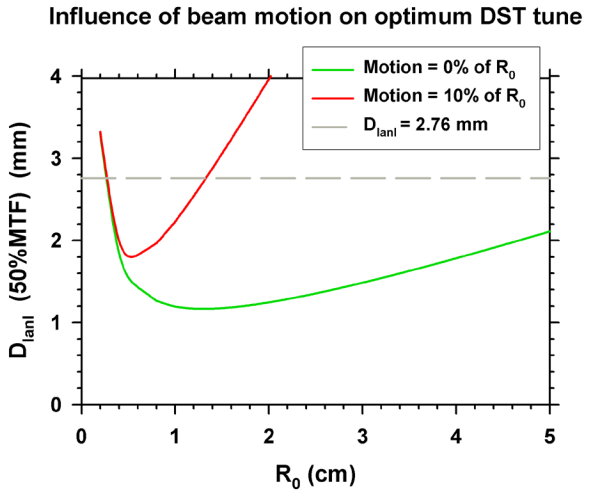
Fundamental Minimum | **Focusing** | **Instabilities**

Beam parameters that are under some degree of control (emittance, energy spread, and beam motion) all contribute to an enlarged spot size.

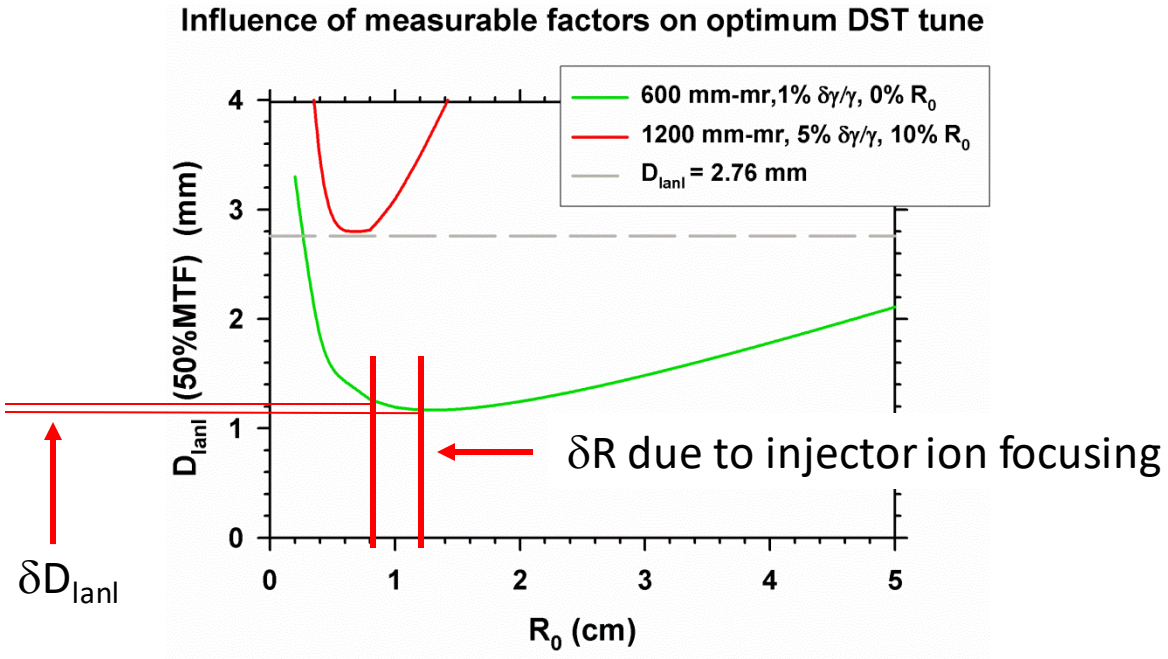
$$r_{spot}^2 = \left(\frac{\varepsilon_n f}{\beta\gamma R_0}\right)^2 + \left(\frac{2\delta\gamma}{\gamma} R_0\right)^2 + \left(C_S R_0^3\right)^2 + \left(\Delta_{\%} R_0\right)^2$$







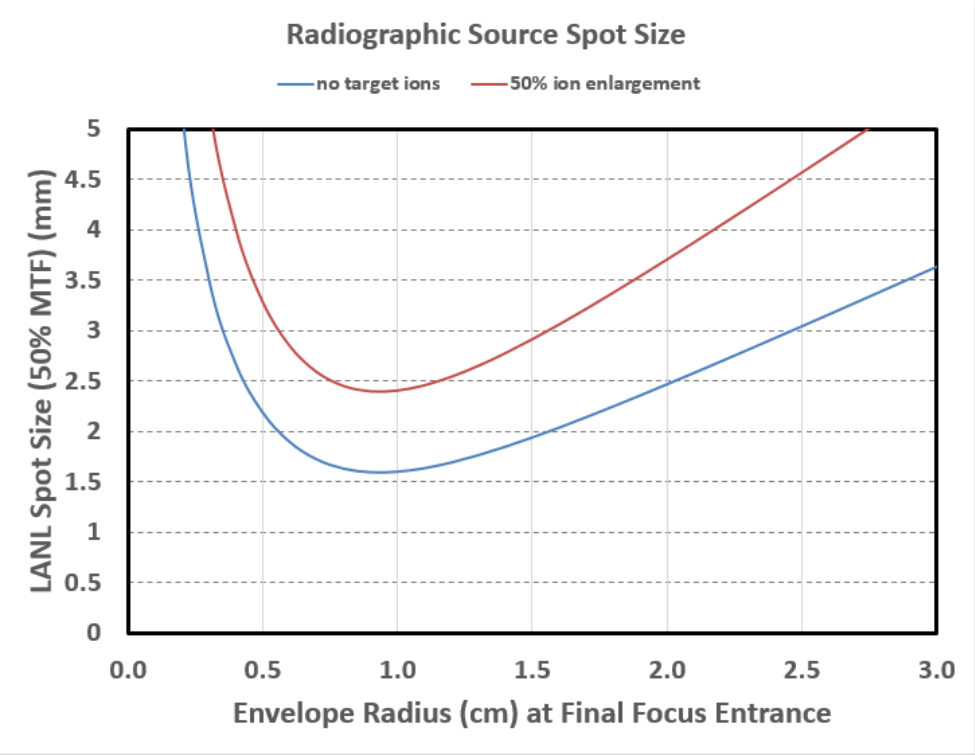
The spot size perturbation due to injector ion focusing can be determined from the perturbation to the beam size at the final focus input.



- Minimum spot achieved when each contributing effect is minimized.
- Diagnostics required for this are emittance, energy and high-frequency motion, at least.
- Spot size can be minimized by tuning the downstream transport for the optimum R_0.
- Target-ion focusing can be empirically accounted for by a multiplicative factor derived from time-resolved spot-size measurements.

Here are some examples based on Trevor's PIC code study of ion effects in the injector.

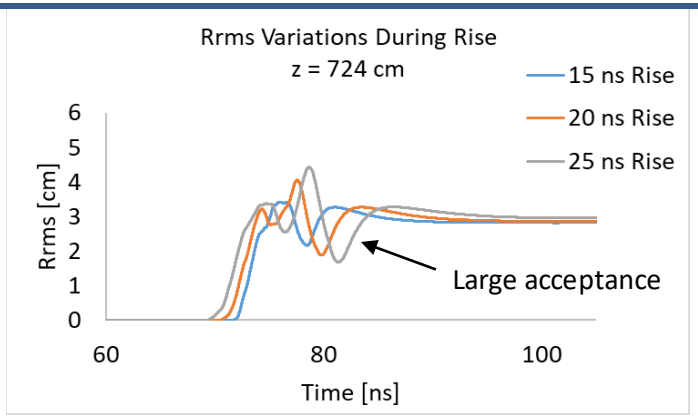
- For these examples, I used a DARHT-II final focus (f =25 cm , C_s = 0.0027132 cm^{-2}), ε_n=1000mm-mrad, $d\gamma/\gamma$ =2%, motion =5% of R_0, based on Trevor's tune of the DST.
- I used 50% enlargement due to ion focusing, based on Trent's data and taking credit for factor of two mitigation of the effect.

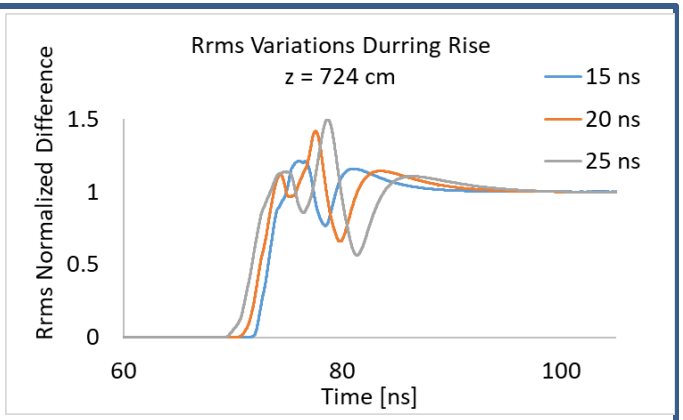


Optimum FF entrance envelope radius is about 1 cm.

No Protons
3 Logistics Functions

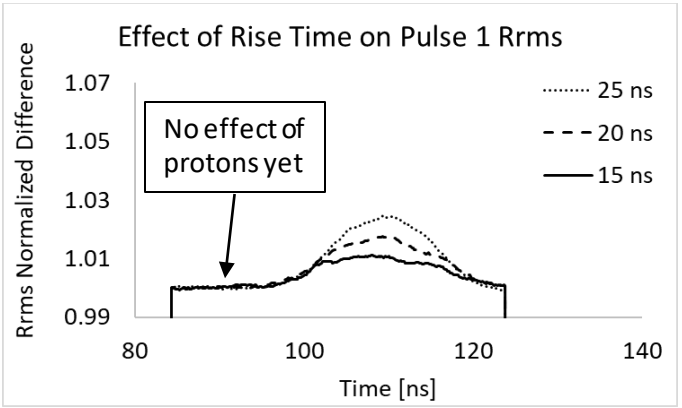
Rrms Variations:
- Short Time
- Large Amplitude

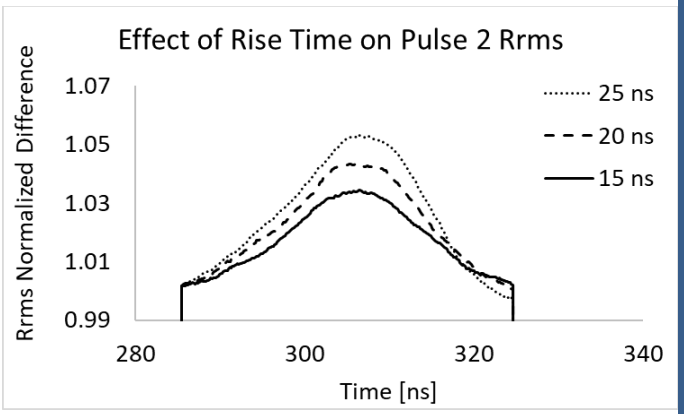


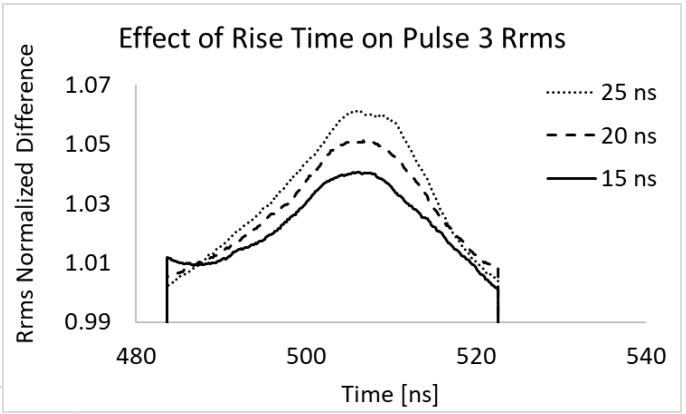


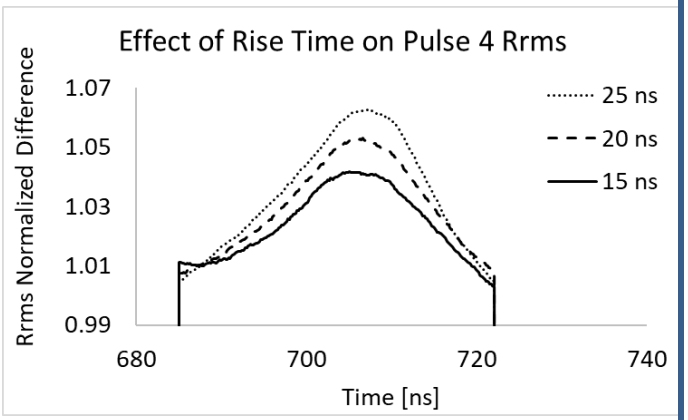
With Protons
Logistics Function

Rrms Variations:
- Long Time
- Small Amplitude



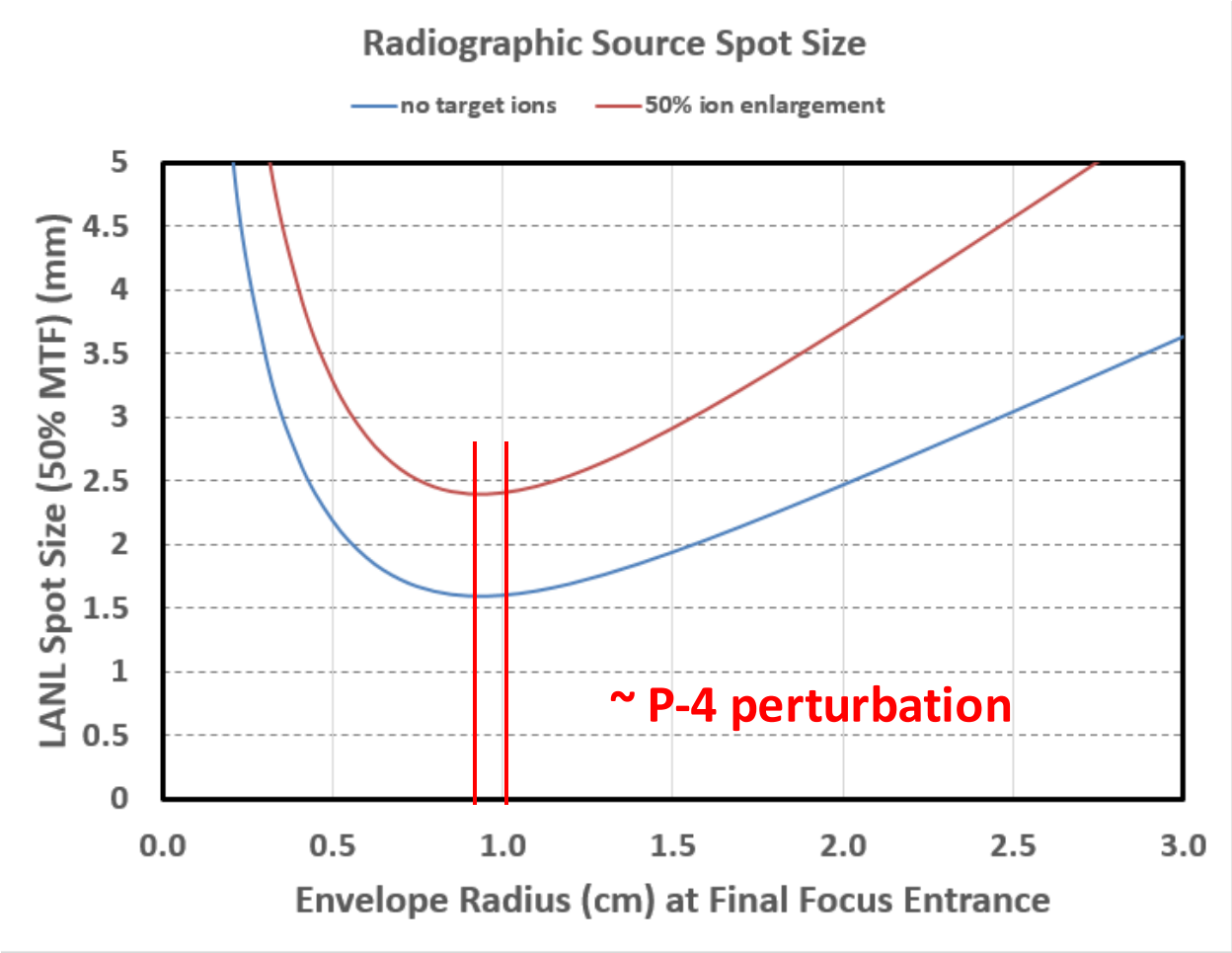






Here are some examples based on Trevor's PIC code study of ion effects in the injector.

- If only protons affect the beam in the anode pipe, the spot is undetectably enlarged.



The fractional enlargement of the source spot by perturbed beam envelope is minimized by tuning for optimum R_0 at final focus solenoid.

Beam Parameters Meeting Requirements:

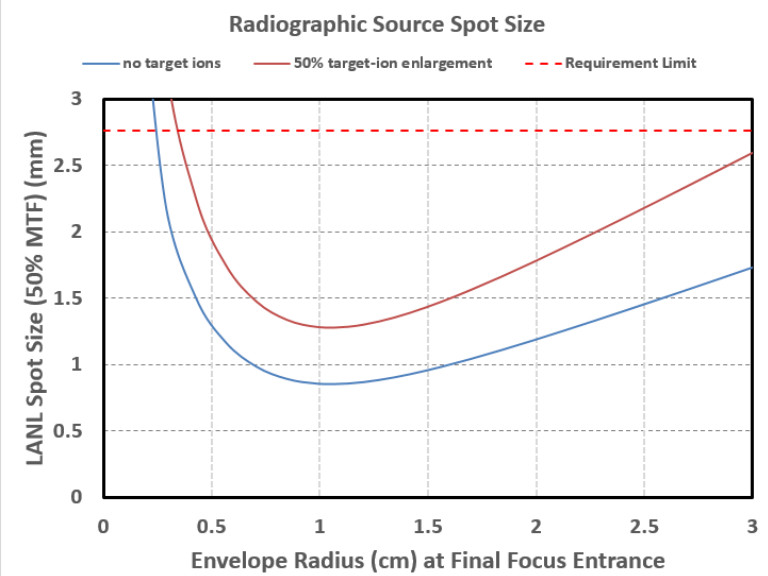
- ε_n = 600 mm-mr
- $d\gamma/\gamma$ = 1.5%
- Motion = 5%

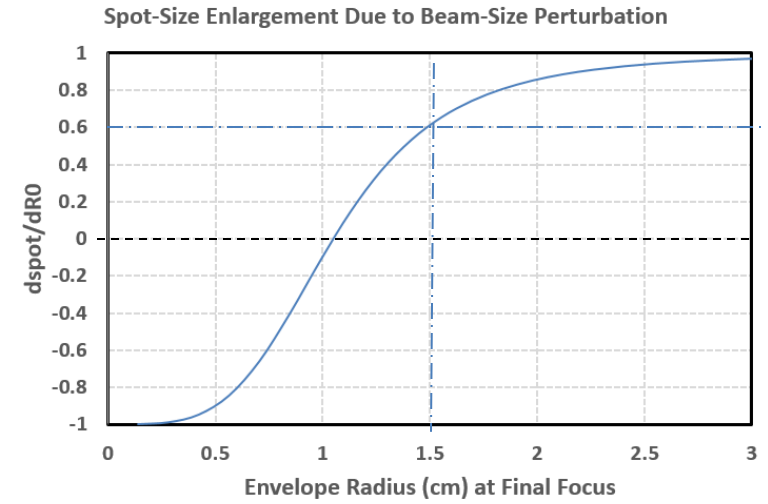
Final Focus (DARHT-II):

- f = 25.1 cm
- C_1 = 0.0027132 /cm^2

Example:
If R_0 is < 50% greater than optimum, a 10% perturbation on beam size gives < 6% enlargement of source spot.

N.B. R_0 < 5 cm will overheat a barrier foil at DARHT-II stand off distance.





Thanks for your attention!